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The Economics of Harvesting and Transporting Hardwood Forest Residue for Conversion to Fuel Ethanol: A Case Study for Minnesota

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The Economics of Harvesting and Transporting Hardwood Forest Residue for Conversion to Fuel Ethanol: A Case Study for Minnesota

by

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Abstract

Forest residues are being considered as potential feedstock for a biomass-to-ethanol facility in Minnesota (USA), using residues from major wood-producing counties in Minnesota, Wisconsin, and Michigan. Results indicate that marginal residue costs delivered to a conversion facility would be $56-80/Mg for a small (95-189 MM liters) plant, and about $81/Mg for a larger (379 MM liters) plant. Output beyond these levels would involve substitution of lower-cost market pulpwood as the plant feedstock because of relatively high marginal residue costs. Sensitivity analysis indicates that either a 20-percent increase or decrease in the quantity of available residue would impact marginal cost estimates by no more than $15/Mg.

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The Economics of Harvesting and Transporting Forest Residue for Conversion to Fuel Ethanol: A Case Study for Minnesota

Introduction

Concerns surrounding the dependence on rogue states for oil as well as the recent spike in oil prices have resulted in widespread efforts to secure new domestic sources of energy. These sources include, but are not limited to, corn ethanol, diesel derived from soybean oil and other fats, and wind, solar, and hydrogen energy. All of these, with the exception of hydrogen energy, are being produced at the commercial scale, albeit in relatively small quantities. Another potential source being studied is biomass. Biomass is defined as any plant or plant-derived material, and includes anything from corn stover and forest residue to animal manure and urban waste (Perlack et al., 2005).

Forest residues (growing-stock tree tops and limbs and non-growing stock bolewood, tops, and limbs) are being considered as potential feedstock for a biomass-to-ethanol conversion facility located in northern Minnesota. This paper ascertains the physical and economic feasibility of utilizing forest residue for such a facility. Considered for this analysis are four plant sizes for the facility, in terms of millions of liters (gallons) of ethanol produced annually: 95 (25), 189 (50), 379 (100), 568 (150), and 757 (200). All estimates are based on a wood-to-ethanol conversion rate of 299.6 liters/Mg (dry). Furthermore, it is assumed that feedstock for the plant would be taken from major wood-producing counties in Minnesota, Wisconsin, and Michigan's Upper Peninsula. This study estimated total forest residue produced and available for harvest in each county. Reported here are estimates of total residue required and marginal costs and transport distances for each plant size, both in terms of dollars per Mg of residue and per liter of ethanol. Market hardwood pulpwood, which is produced widely throughout the study region and is a readily-available substitute for forest residue in the production of ethanol, was chosen as the backstop feedstock. I.e., if sufficient forest residue was unavailable or if the cost of residue collection and transport exceeded the price of market pulpwood, then it was assumed that market pulpwood would be substituted for residue to supply the conversion facility. Residue estimates were then combined with price data for market pulpwood to derive a wood residue/pulpwood supply function for the proposed facility. Finally, sensitivity analysis was run to ascertain the impact of residue availability assumptions on county-level quantities and costs.

Forest Residue

Residue quantities were estimated using 2000-2004 annual county-level volumes of total wood product (Piva, 2006). Data was divided into two categories, aspen and all other hardwoods, and the 5-year average of each were used as the base cases. See Table 1 for conversion rates and other parameter values. Variation in annual yield was tested in sensitivity analysis later. Residue quantities available were estimated as follows. Miles, Chen, and Leatherberry (1992) report totals for all live tree biomass on timberland for hardwood species by biomass component for Minnesota for the year 1990. The percentage of total biomass was calculated for each tree component (see Table 2). Then the shares for growing-stock tops and limbs (16%), and non-growing stock boles (12%) and tops and limbs (3%) were summed (31%), and this share was considered the share available as residue. To be able to estimate residue quantities as a function of roundwood product, this share was then divided by the share attributed to growing-stock boles (53%), to arrive at an estimate of the share of total tree biomass that can be considered residue based on the quantity of growing-stock boles (i.e., roundwood product) (59%). This method is similar to that used by Berguson, Buchman, and Maly (2005). For the analysis, this percentage was applied to two scenarios: one that considered only aspen, and one that considered all hardwood species.

Following Berguson, Buchman, and Maly (2005), the totals based on the above estimates were then reduced by an arbitrary 25 percent to provide waste for nutrient replenishment and wildlife habitat, as well as other miscellaneous losses that occur during the harvest process. Furthermore, estimates were reduced by a percentage representing the rate of participation in residue harvest by forestland owners. Because no information is available regarding willingness to participate, an arbitrary rate of 75 percent was assumed for the amount of forestland actually available for harvest in the base case. Thus, the figures for total residue collected for each county for the base case is equal to 1 x 0.59 x 0.75 x 0.75 = 0.33 of total roundwood product. Berguson, Buchman, and Maly (2005) argue that non-growing stock trees not be included in the quantity of residue available. Following this argument, the above 59 percent figure would be reduced to 30 percent, for a net share of 1 x 0.30 x 0.75 x 0.75 = 0.17. These assumptions were tested for sensitivity later in the analysis.

Next, it was decided that a threshold be used to exclude harvest from sparsely populated counties, where it was assumed that harvest would be relatively expensive and perhaps physically infeasible. The threshold used was that a given county must have 18,144 Mg (green) available for a given year, after accounting for all of the aforementioned deductions.

Harvest costs were taken from Burguson, Maly, and Buchman (2002), and adjusted for inflation. They estimated costs of owning and operating a chipping and a grinding system for forest harvest residues in northern Minnesota. Although grinding is more expensive per Mg, they noted that residue which has been piled at a landing over a period of time is likely to contain a greater share of dirt than residue that has been chipped immediately. It is believed that this additional dirt is likely to dull the chipper knives quickly and that maintenance would be too high to justify using a chipper this way. Therefore, for this analysis, the grinding method was assumed. A loader would also be needed for the operation, and total grinding costs, including procurement, loader, and stacking costs, was estimated at $9.43/Mg (green). Stumpage cost for residue is assumed to be $5.90/Mg (green). Thus, total costs, before transportation, for the grinding method was estimated at $15.33/Mg (green). Costs were not location specific; therefore, per-Mg harvest cost is identical for each county.

Transportation costs were estimated using the shortest highway distance from each county seat to the proposed conversion facility location of Hibbing, Minnesota. For Minnesota counties, travel distance was taken from the Official Minnesota Highway Mileage Tables (1976), and for Michigan and Wisconsin counties, travel distance was taken from the Rand-McNally online distance calculator (2006). In the absence of logging-specific transportation costs, costs per loaded km were taken from the USDA-AMS Grain Transportation Report (2006), which estimates costs at $2.24, $1.46, and $1.18 per loaded km for one-way trips of 0-40, 41-161, and >161 km, respectively. These trucking costs are consistent with those reported by Burguson, Maly, and Buchman (2002). It was assumed that each truck was able to transport 24.9 Mg of chips (green) per load.

Market Pulpwood

A substitute for hardwood residue in the biomass-to-energy process is market pulpwood. It is expected that at some quantity level, the price of residue (assumed to be equal to the delivered cost estimated above) will approach, equal, and eventually surpass that of market pulpwood. Thus, it is at this critical quantity level that feedstock demand from the conversion facility would switch from purchasing additional residue to purchasing market pulpwood. Hence, the market pulpwood price would serve as the backstop price for the wood feedstock market for the proposed facility.

Price estimates for U.S. market pulpwood were taken from the 2005 *Pulp & Paper Global Fact & Price Book.* The average delivered price of hardwood roundwood pulpwood during the first half of 2005 was $82/Mg (dry) (Pulp and Paper, 2005). Assuming that market pulpwood would arrive at the plant in log form, it would be necessary to chip or grind the logs before use in the conversion facility. A grinding cost of $8/Mg (dry) was assumed, which is consistent with the reported grinding costs for field operations (Burguson, Maly, and Buchman, 2002). Therefore, cost of chipped market pulpwood at the plant was assumed to be $90/Mg (dry).

Results

Figure 1 illustrates the distribution of counties from which residue would be harvested for each plant size under the aspen-only scenario. A 95-millon liter (25MM[1] gal) plant could be supplied by 5 counties, whereas a 189MM liter (50MM gal) plant would draw residue from 7 additional counties. A 379MM liter (100MM gal) plant would draw from 40 additional counties. Under the aspen-only scenario a facility of 568MM liter (150MM gal) or greater would need to supplement its feedstock supply with market pulpwood because sufficient residue would not be available in the study region under the base-case assumptions.

Table 3 contains the corresponding total residue required, marginal cost estimates, and marginal residue transport distance for each plant size. At the 95-millon liter (25MM gal) plant size, marginal cost of residue would be $58/Mg (dry), or $0.19/liter ethanol ($0.73/gallon). Marginal transport distance would be 171 km. Marginal cost would increase to $80 for the 189MM liter (50MM gal) facility, which corresponds to per-liter (per-gallon) costs of $0.27 ($1.01). The corresponding marginal transport distance would be 213 km. For the 379MM liter (100MM gal) facility, sufficient residue would be available, but the marginal cost of residue

[1] The letters "MM" is shorthand for "millions".

would exceed that of market pulpwood; consequently demand would shift to market pulpwood at $90/Mg.

If all hardwood species are considered for residue collection, then the above figures are tempered somewhat, and higher plant output is feasible. Figure 2 shows the range of counties from which residue would be drawn under this scenario. The 95-millon liter (25MM gal) facility could be supplied by 3 counties rather than 5, relative to the aspen-only scenario. The 189MM liter (50MM gal) facility could be supplied by 4 fewer counties, and the 379MM liter (100MM gal) facility, by 21 fewer. Marginal transport distance would fall by 42, 27, and 239 km for the 95MM (25MM), 189MM (50MM), and 379MM (100MM) liter (gallon) facilities, respectively (see Table 3). The 568MM liter (150MM gal) and 757MM liter (200MM gal) facilities, which were infeasible under the aspen-only scenario, would be supplied by residue from 51 and 76 counties, respectively. Marginal transport distance for the 568MM liter (150MM gal) and 757MM liter (200MM gal) facilities would be 470 and 602 km, respectively.

In dollar terms, marginal cost would fall by $2 and $19/Mg for the 95-millon liter (25MM gal) and 189MM liter (50MM gal) facilities, respectively, or by $0.00 ($0.02) and $0.07 ($0.24) per liter (gallon) of ethanol. Marginal costs for the 379MM liter (100MM gal) plant need to be compared to the market pulpwood price, not the aspen-only scenario cost. Under this comparison, all-hardwood residue would have a $9/Mg ($0.02/liter, $0.10/gal) marginal-cost advantage over market pulpwood. Finally, although sufficient residue quantities would be available to supply the 568MM liter (150MM gal) and 757MM liter (200MM gal) facilities, marginal cost would exceed $90/Mg, and thus market pulpwood would be the lower-cost, and hence, preferred, feedstock at these output levels.

Thus, based on this analysis, market pulpwood would comprise part of the feedstock supply for the 379MM liter (100MM gal) facility and would be required to achieve any output greater than that under an aspen-only scenario. For the all-hardwoods scenario, market pulpwood would comprise part of the feedstock supply for the 568MM liter (150MM gal) and 757MM liter (200MM gal) plants. These results are illustrated in Figure 3, which shows a residue/market-pulpwood supply curve under the aspen-only and all-hardwoods scenarios.

Sensitivity Analysis

All of the results presented above were dependent on the assumptions used to estimate quantities of residue available in a given county, which were based on a percentage of harvested roundwood product. Furthermore, these quantities were affected by what tree biomass components were included as residue. This work included non-growing-stock bolewood, tops, and limbs as part of the residue estimates. Others have argued, however, that non-growing stock should not be included as available residue (Berguson, Buchman, and Maly, 2005).

Additionally, the share that must be left in the stand due to conservation concerns, the share that is lost during harvest and transport, and the participation rate of forestland owners further complicate these estimates. Ultimately, however, these factors can be conceived of as a single factor that determines the "effective share" of forest biomass that is available as residue in a given location. As noted earlier, the effective share under the base case was equal to 1 x 0.59 (residue as share of roundwood product) x 0.75 (share available due to conservation/harvest losses) x 0.75 (participation rate) = 0.33 of total roundwood product. Excluding non-growing stock trees would result in an effective share of 1 x 0.30 (residue share excluding NGS) x 0.75 x 0.75 = 0.17. Similarly, one could assume an alternative participation rate and conclude that the effective share is some other value.

The point here is that all of these assumptions impact the same bottom-line figure, and hence, they need not be analyzed separately in order to understand the impact that would result from variations in their values. Following this argument, then, sensitivity analysis was carried out by estimating supply functions under alternative effective share values: 50, 40, 33 (the base case), 20, and 10 percent. Thus, the 50-percent case, for example, represents the most optimistic case regarding how much residue is available, and the 10-percent case, the most pessimistic. This analysis was run for both the aspen-only and all-hardwoods scenarios.

Finally, because wood harvest quantities vary annually, analysis was carried out to ascertain the sensitivity of the results to using annual-average quantity data. This was done by estimating supply functions for each individual year of data (2000-2004) and comparing these results to the base case (5-year average). This analysis was also run for both the aspen-only and all-hardwoods scenario.

Sensitivity Analysis Results

Figure 4 plots the wood feedstock supply functions for alternative effective share values under the aspen-only scenario. Under the base case, where effective share was assumed to be 33 percent of total roundwood product, 295.3MM liters (78.0MM gals) of ethanol could be produced from aspen residue before marginal cost reached the market pulpwood price of $90/Mg, where feedstock demand was assumed to switch over to pulpwood. Under the 10- and 20-percent effective-share assumptions, however, 90.6MM liters (23.9MM gal) and 177.2MM liters (46.8MM gal) of ethanol could be produced from aspen residue before marginal cost reached the market pulpwood price, respectively. Under the more optimistic effective-share assumptions of 40 and 50 percent, 354.4MM liters (93.6MM gal) and 445.0MM liters (117.5MM gal), respectively, could come from aspen residue prior to marginal cost reaching the market pulpwood price. Thus, under the most pessimistic share assumption, even the smallest plant (95MM liters, 25MM gal) would supplement its feedstock supply with market pulpwood and hence have a marginal cost of $90/Mg, whereas under the most optimistic assumption, aspen residue could fully supply the 379MM liter (100MM gal) plant at a marginal cost of $77/Mg. Even under the most optimistic assumption, however, the 568MM liter (150MM gal) and 757MM liter (200MM gal) plants would supplement their feedstock supply with market pulpwood, at a marginal cost of $90/Mg.

Figure 5 plots wood feedstock supply functions for each alternative effective-share value under the all-hardwoods scenario. Because this scenario includes all hardwoods, quantities presented here will be everywhere greater than those presented for the aspen-only scenario. Under the base case, where effective share was assumed to be 33 percent of total roundwood product, 441.7MM liters (116.7MM gals) of ethanol could be produced from all-hardwood residue before marginal cost reached the market pulpwood price of $90/Mg. Under the 10- and 20-percent effective-share assumptions, however, 135.4MM liters (35.8MM gal) and 265.0MM liters (70.0MM gal) of ethanol could be produced from hardwood residue before marginal cost reached the market pulpwood price, respectively. Under the more optimistic effective-share assumptions of 40 and 50 percent, 530.0MM liters (140.0MM gal) and 665.5MM liters (175.8MM gal), respectively, could come from hardwood residue prior to marginal cost reaching the market pulpwood price. Thus, under the most pessimistic share assumption, only the smallest plant (95MM liters, 25MM gal) would satisfy its entire feedstock supply with hardwood residue, at a marginal cost of $71/Mg, with all larger plants supplementing supply with market pulpwood, and hence facing a marginal cost of $90/Mg. Under the most optimistic assumption, however, all but the largest plant could satisfy feedstock supply with hardwood residue at marginal costs of $41/Mg (95MM liter, 25MM gal), $58/Mg (189MM liter, 50MM gal), $66/Mg (379MM liter, 100MM gal), and $81/Mg (568MM liter, 150MM gal). For the largest plant, 665.5 of the total 757MM liters (175.8MM of the total 200MM gal) would come from hardwood residue, with the remaining ethanol derived from pulpwood; marginal cost would thus be $90/Mg.

The next method of testing for sensitivity in the results was done by examining how marginal costs changed when each year of data was used individually, and comparing these results to the base-year results which were based on the 5-year average. Figure 6 plots wood feedstock supply functions based on each individual year of quantity data, as well as the base-case (the 5-year average), under the aspen-only scenario. Marginal cost was essentially unaffected by year assumption at the 95MM liter (25MM gal) and 189MM liter (50MM gal) plant output levels. The greatest variation came in the 250-300MM liter output range, where marginal aspen residue cost ranged from a low of $70/Mg (year 2000) to a high of $90/Mg (years 2003 and 2004), with an average (base-case) marginal cost around $85/Mg. At the highest plant output levels, marginal cost was unaffected by year assumption because at these levels the market pulpwood price set the marginal cost under all year assumptions. Thus, results indicate that using the 5-year average of quantities of aspen residue did not substantially affect the results.

Figure 7 plots the wood feedstock supply functions for each individual year of quantity data, as well as the base-case (the 5-year average), under the all-hardwoods scenario. Marginal hardwood residue cost was not much affected by year assumption at the 95MM liter (25MM gal) and 189MM liter (50MM gal) plant output levels. The greatest variation came in the 300-350MM liter output range, where marginal cost ranged from just under $70/Mg (year 2000) to a high of $80/Mg (year 2001). Results were unaffected by year assumption at output beyond 450MM liters because marginal cost was set by the market pulpwood price under all year assumptions. Thus, as in the aspen-only scenario, results indicate that using the 5-year average of quantities of hardwood residue did not substantially affect the results.

Conclusions

The results reported here indicate that a plant producing between 95MM and 189MM liters (25MM and 50MM gal) of ethanol per year could do so using only hardwood residue at a marginal cost below the price of market pulpwood. A plant producing 379MM liters (100MM gal) per year could do so if it utilized residue from all hardwood species, and if the effective share of biomass as residue was at least 30 percent. Plants producing in excess of 379MM liters (100MM gal) would likely need to supplement their residue feedstock supply with an alternative wood feedstock, such as market pulpwood, as indicated here.

Results also indicate that residue feedstock costs delivered to a conversion facility would be $56-80/Mg for a small (95-189MM liters) plant, and about $81/Mg for a larger (379MM liters) plant. At greater output levels, the marginal cost of collecting and transporting residue would exceed the price of market pulpwood, and hence at these quantities demand would shift to pulpwood at a marginal cost of $90/Mg. Sensitivity analysis indicates that either a 20-percent increase or decrease in the value of the effective share of total biomass as residue would result in a change in marginal cost of no more than $15/Mg. Furthermore, sensitivity analysis indicates that annual variation in forest production could impact marginal costs by +/- $5/Mg under the aspen-only scenario and +/- $3/Mg under the all-hardwoods scenario.

Whether the costs indicated here are sufficiently low to allow for a profitable wood-to-ethanol plant to exist is another question. The answer to such a question would require a detailed analysis of plant operations, including investment and operating costs, and market opportunities for plant output. This work simply indicates how much residue would be required for a range of typical plant sizes, whether such quantities would be available under reasonable assumptions, and how much it would cost to acquire these residues for a facility in northern Minnesota. Further, using average market pulpwood price as a feedstock "backstop" price, this work shows how much residue could be harvested before marginal cost would exceed that of a substitute feedstock, and hence, render collection of additional residue economically infeasible as a fuel feedstock for the proposed plant location.

However, a simple comparison can be made to corn grain, the dominant ethanol feedstock in the United States.[2] Nicola (2005) estimated production costs between \$0.33 and \$0.38/liter (\$1.26 and \$1.42/gal) for a typical 189MM liter (50MM gal) corn-to-ethanol conversion facility. Wooley et al. (1999) estimated production costs, excluding feedstock, for a 198 liter (52.2 MM gal) wood-to-ethanol conversion facility between \$0.26 and \$0.34/liter (\$0.99 and \$1.27/gal). Adding to their result the estimated marginal cost of wood residue for the 50MM gal plant reported here, the estimated production cost for a wood-to-ethanol facility would range between \$0.46 and \$0.54/liter (\$1.76 and \$2.04/gal). Thus, using this simple comparison, it is apparent that the low estimate of costs for ethanol from wood residue is just a few cents higher than that of the high for ethanol from corn grain. Therefore, it is likely that some combination of cost reductions and technological improvements in the wood-to-ethanol conversion process would reduce these costs and make ethanol from wood residue cost competitive with that of corn grain. It should be noted, however, that costs for ethanol derived

[2]Because the location of the facility in the heart of hardwood production would be far removed from that of corn, transport costs for corn would likely preclude it as a ready substitute feedstock. The comparison, however, is still valid and informative.

from market pulpwood would range between \$0.51 and \$0.59/liter (\$1.92 and \$2.20/gal), and thus present a greater hurdle in terms of competing with ethanol derived from corn grain.

It is likely that pulpwood production and prices in this region will change substantially over the coming years. Further, if the current trend toward renewable fuels continues and forest residue catches on as a viable feedstock, harvest methods will become more efficient and stumpage prices will likely rise. All of these changes will significantly alter the relative costs of these feedstocks. Research into such market scenarios is in order.

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Table 1. Base-case parameters used for forest residue collection and transport analysis.

Residue Harvest Year	2000-04 Average
Wood Species Considered	Aspen; All Hardwoods
Forestland Participation Rate	75%
County Residue Minimum Threshold, Mg/year (green)	18,144
Residue as % of Roundwood Product	59%
Residue as % of Roundwood Product (excl. NGS)	30%
Wildlife/Nutrient mitigation/Other Deduction	25%
Residue to Ethanol Conversion Rate, liters/Mg (bone-dry)	299.6
Grinder Cost, per Mg	\$4.06
Loader cost, per Mg	\$2.30
Procurement cost, per Mg	\$0.71
Cost for logger to stack residue on-site, per Mg	\$2.36
Residue stumpage cost, per Mg	\$5.90
Cargo weight, Mg	\$24.9
Cost per loaded km (semi-hauled) (40 km)	\$2.24
Cost per loaded km (semi-hauled) (41-161 km)	\$1.46
Cost per loaded km (semi-hauled) (>161 km)	\$1.18
Pulpwood Price, delivered, per Mg	\$82
Pulpwood Chipping cost at plant, per Mg	\$8
Mg (green) per m^3 (Aspen)	0.95
Mg (green) per m^3 (all other hardwoods)	0.96 (average)
dry weight to green weight ratio	0.54

Table 2. All hardwood live-tree biomass on timberland by tree biomass component for Minnesota, 1990 (Miles, Chen, and Leatherberry, 1992)

Components	**% Share**	**Mg (green)**
All Live 1-5" Trees	11%	66,064,810
Growing-stock Stumps	4%	23,246,638
Growing-stock Boles	53%	308,128,822
Growing-stock Tops & Limbs*	16%	92,697,740
Non-growing-stock Stumps	1%	5,078,303
Non-growing-stock Boles*	12%	70,426,938
Non-growing-stock Tops & Limbs*	3%	19,639,540
Total	**100%**	**585,282,791**
Residue as % of Growing-stock Boles:	59%	
Residue as % of Growing-stock Boles (excl. NGS)	30%	

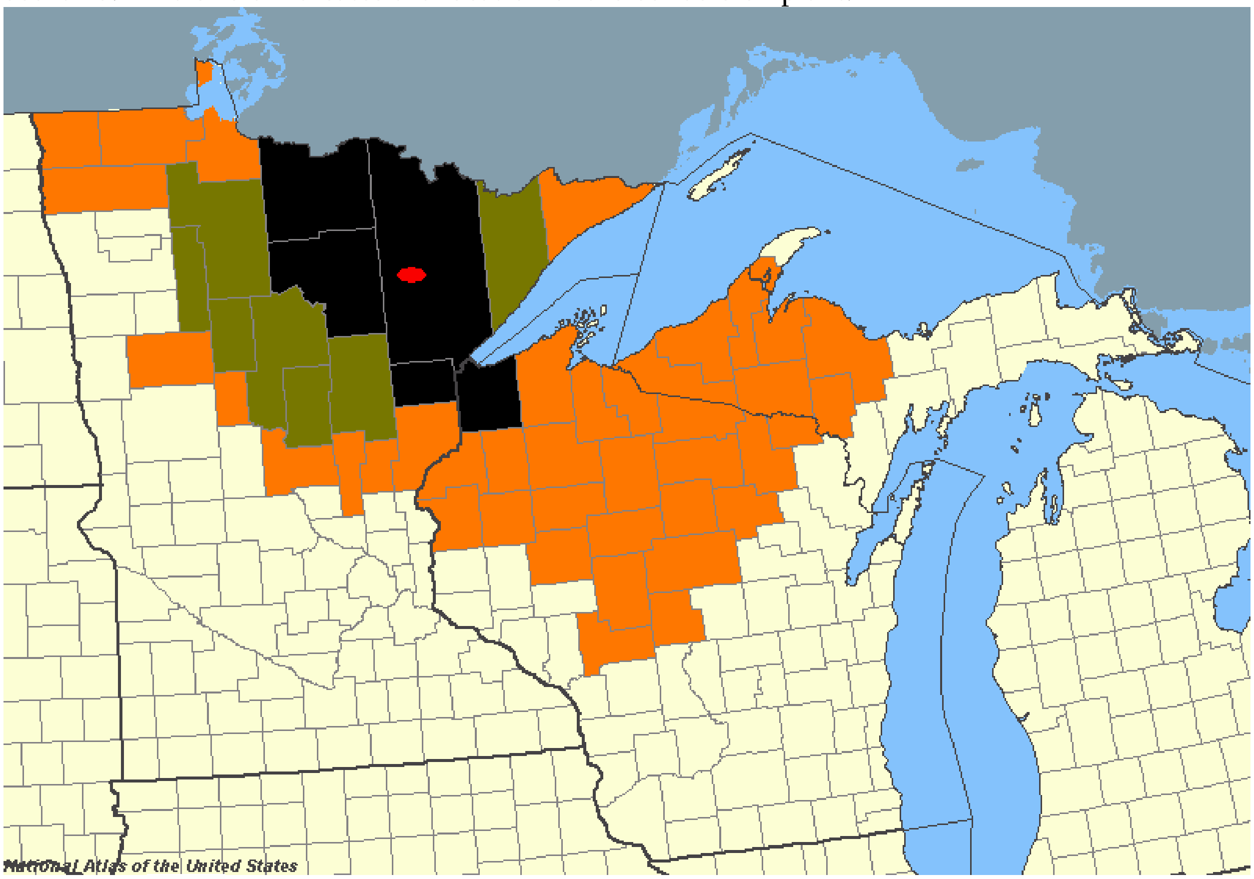
* Considered as residue

Table 3. Marginal Costs for each plant size under the aspen-only and all-hardwood scenarios.

Plant Size, MM liters/yr ethanol (MM gal/year)	**Residue Required (dry Mg)**	**Marginal Delivered Residue Cost, $/Mg (dry)**		**Marginal Share of Ethanol Cost, $/liter ($/gallon)**		**Marginal Transport Distance, km**	
		Aspen	*All Hardwood*	*Aspen*	*All Hardwood*	*Aspen*	*All Hardwood*
95 (25)	315,893	$58	$56	$0.19 ($0.73)	$0.19 ($0.71)	171	129
189 (50)	631,786	$80	$61	$0.27 ($1.01)	$0.20 ($0.77)	213	186
379 (100)	1,263,572	$123*	$81	$0.41 ($1.56)	$0.27 ($1.03)	542	303
568 (150)	1,895,358	Infeasible	$111*	Infeasible	$0.37 ($1.40)	Infeasible	470
757 (200)	2,527,144	Infeasible	$134*	Infeasible	$0.45 ($1.69)	Infeasible	602

*Assuming a market pulpwood price of $90/Mg, the pulpwood price would prevail at this quantity, not the cost shown. In terms of ethanol, market pulpwood cost of $90/Mg is equivalent to $0.25/liter ($0.93/gal).

Figure 1. Counties used as sources of wood residue for each plant size, under the aspen-only scenario. The circle indicates the location of the conversion plant.



25MM 50MM 100MM

Figure 2. Counties used as sources of wood residue for each plant size, under the all-hardwoods scenario. The circle indicates the location of the conversion plant.

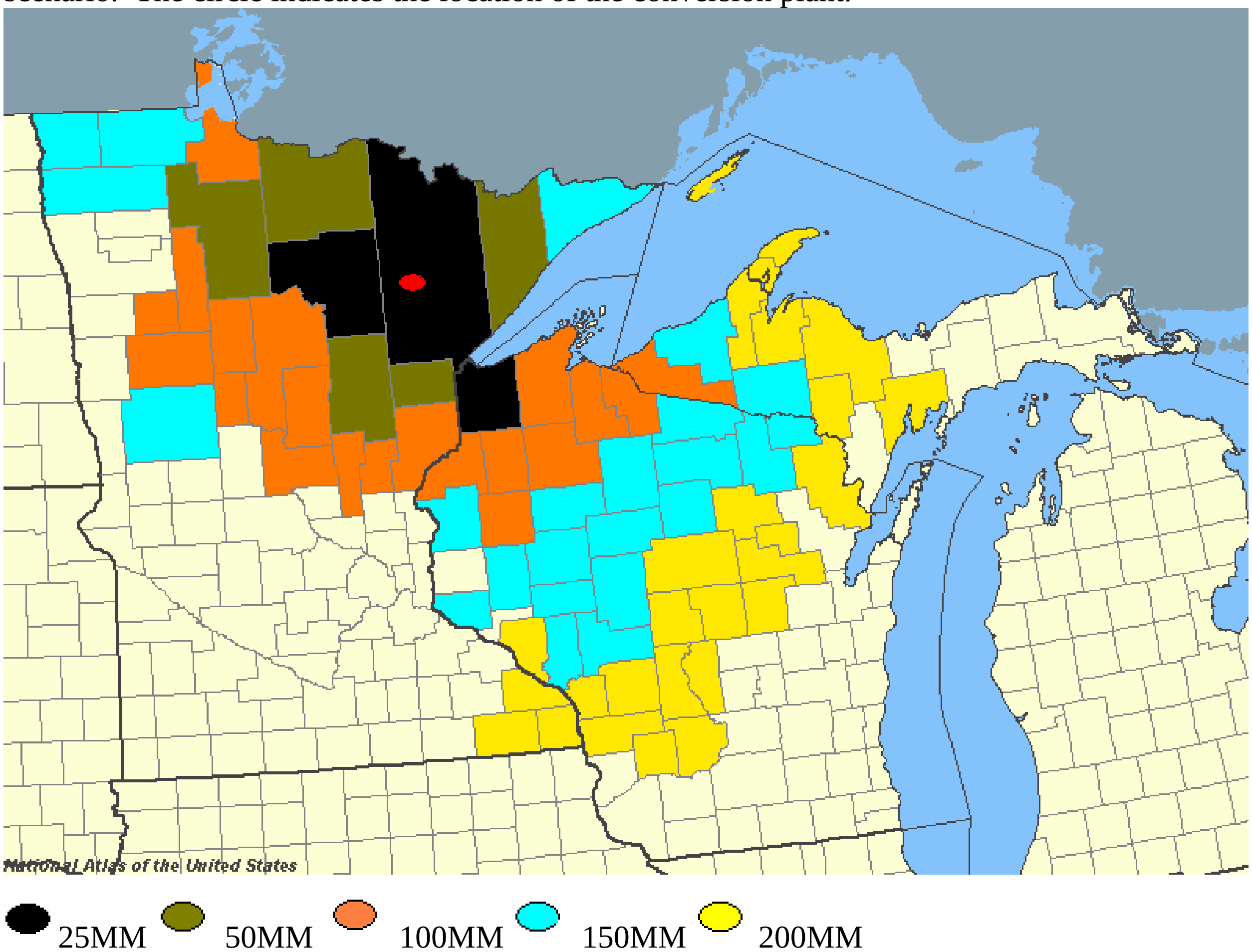


Figure 3. Residue/Market-Pulpwood Supply Curve for Minnesota Biomass Facility, aspen-only and all-hardwoods scenarios.

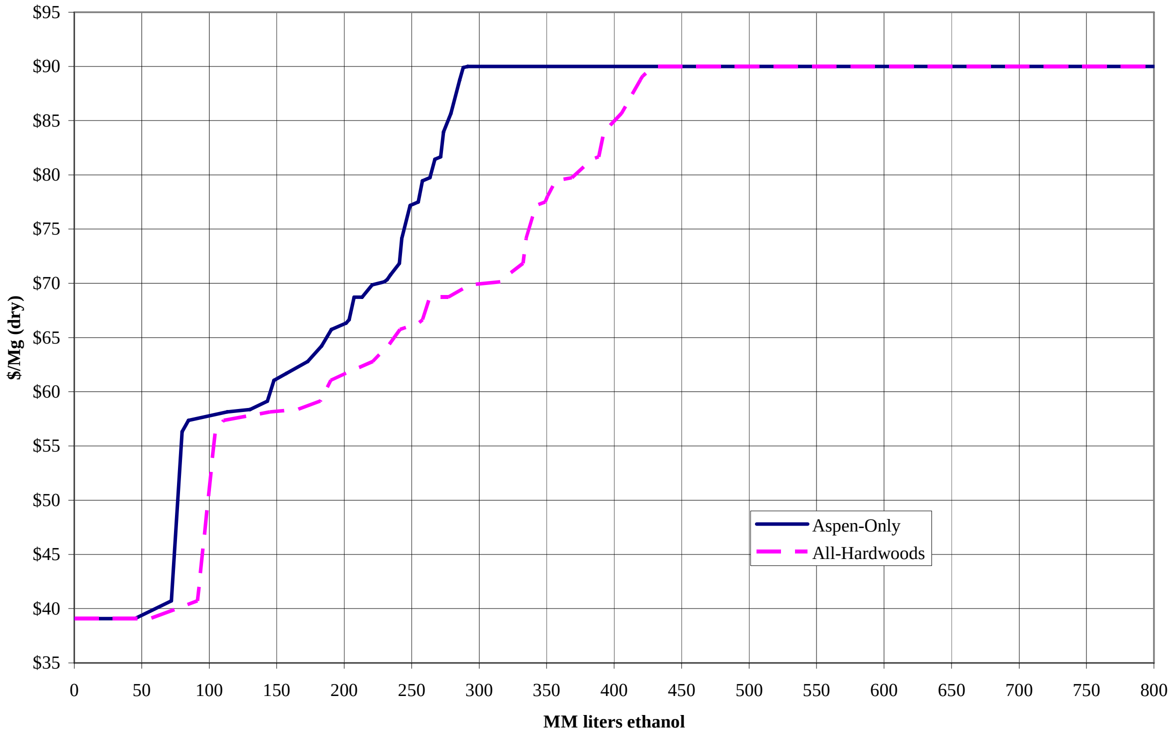


Figure 4. Sensitivity Analysis of Residue/Market-Pulpwood Supply Curve for Minnesota Biomass Facility, aspen-only scenario, under alternative effective share percentages.

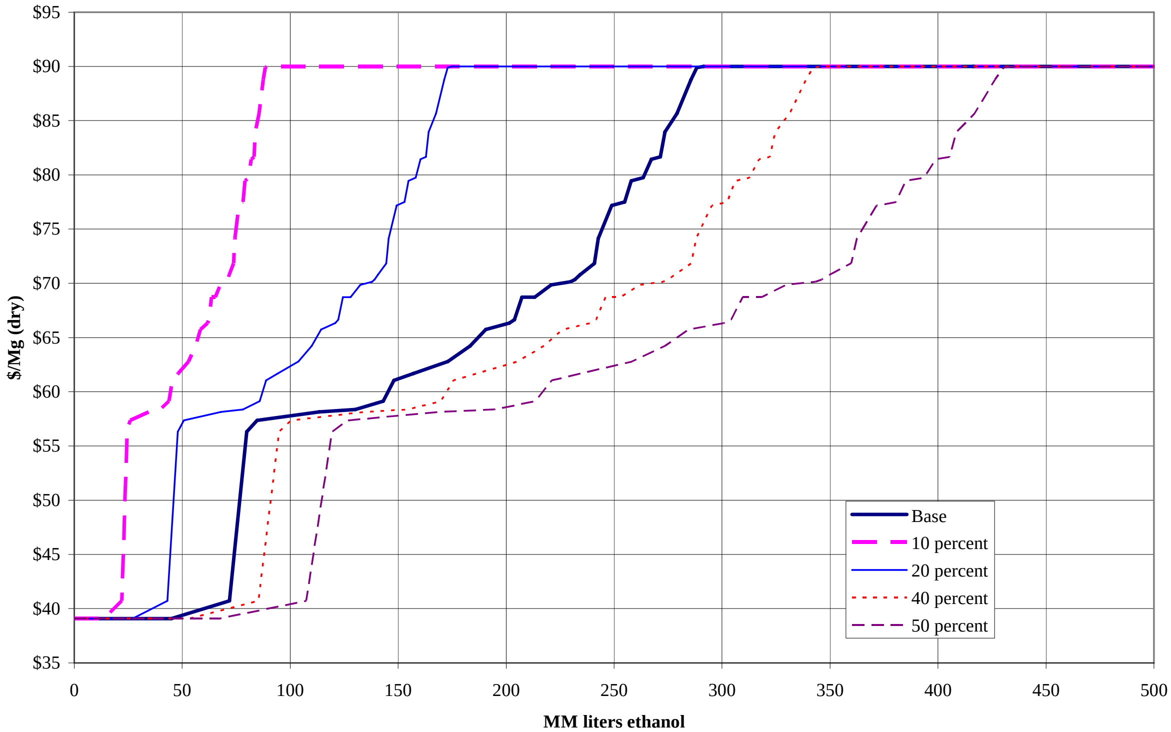


Figure 5. Sensitivity Analysis of Residue/Market-Pulpwood Supply Curve for Minnesota Biomass Facility, all-hardwoods scenario, under alternative effective share percentages.

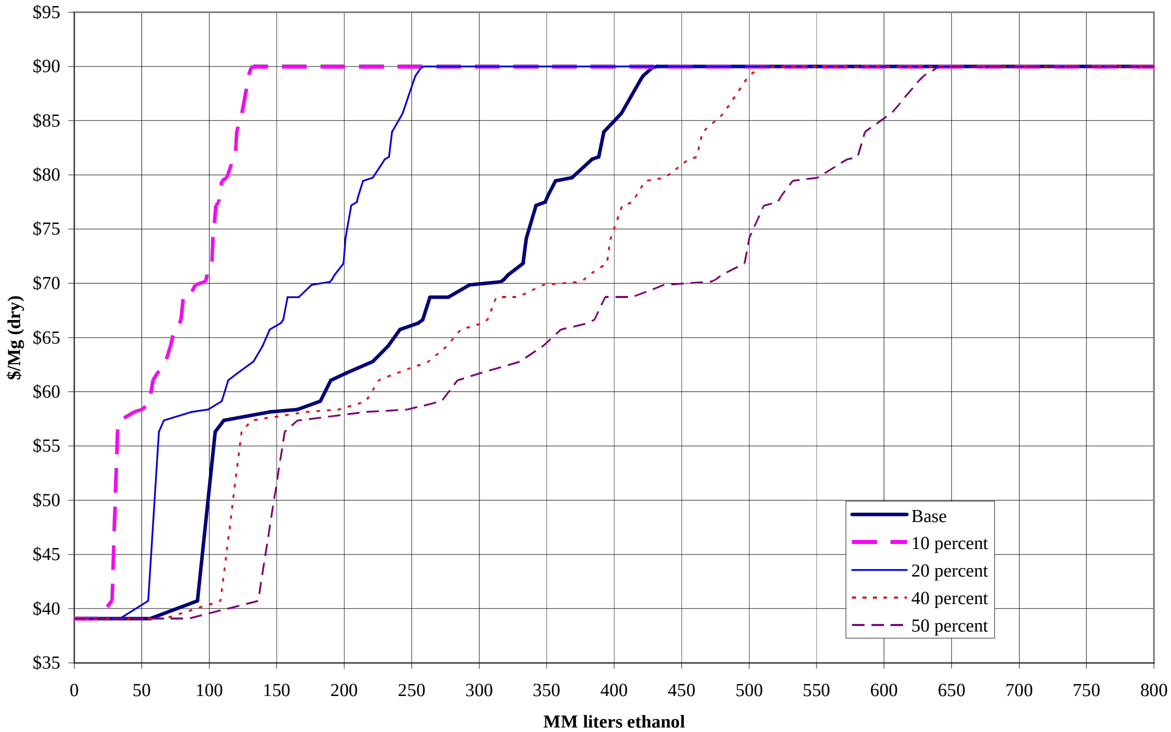


Figure 6. Sensitivity Analysis of Residue/Market-Pulpwood Supply Curve for Minnesota Biomass Facility, aspen-only scenario, under alternative data years.

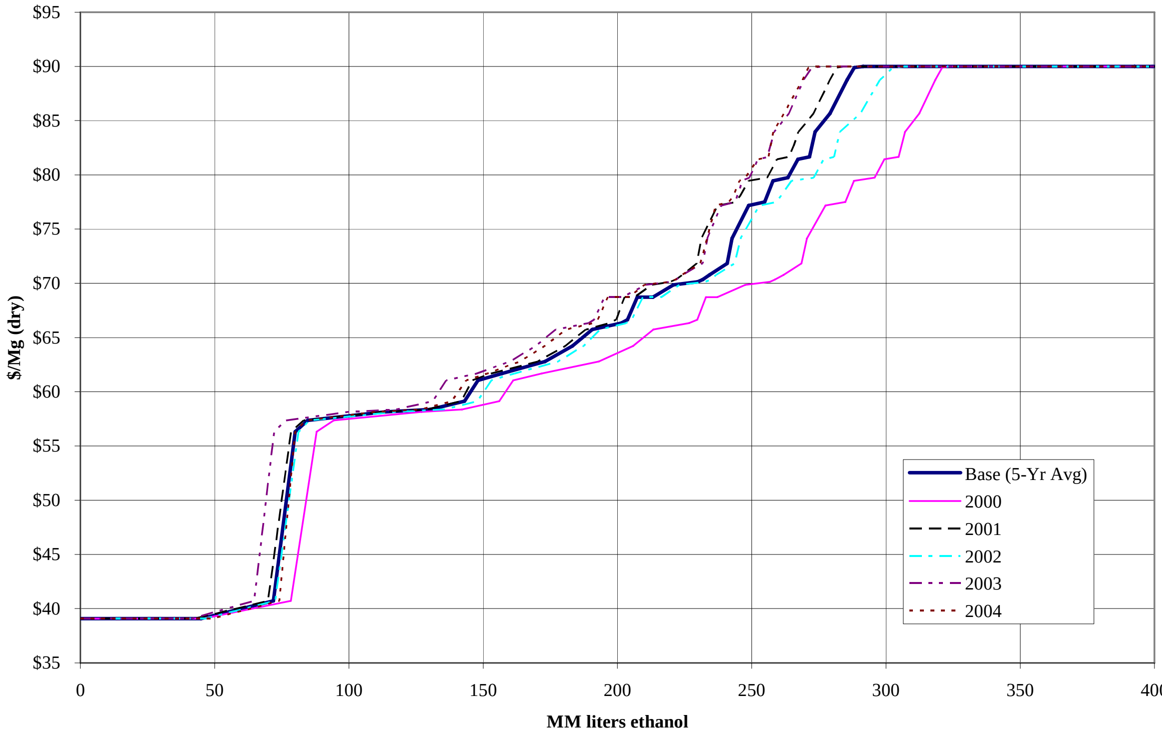


Figure 7. Sensitivity Analysis of Residue/Market-Pulpwood Supply Curve for Minnesota Biomass Facility, all-hardwoods scenario, under alternative data years.